



Parametric Energy Simulation of High-Rise Multi-Family Housing

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Toward Pre-Simulated Guidelines for Low-Energy High-Rise Residential Design in Megacities

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ABSTRACT

In order to improve early decision-making for similar projects, the authors used parametric energy simulation with the eventual aim of providing pre-design guidance for multiple teams of architects and policy-makers. The authors investigated high-rise, multi-family residential buildings in three megacities as case studies. They tested the impact of various design parameters on different energy objectives that they anticipate including in their pre-design resource. The research included three parts. (1) The authors identified synergies and trade-offs, in terms of early design decisions, when designing for different energy objectives, including (a) reducing annual energy consumption, (b) shaving peak-energy demand, and (c) increasing passive survivability – i.e., maintaining the safest interior temperatures in an extended power outage. (2) They performed sensitivity analyses to identify the impact of various design parameters – which included building form, window-to-wall ratio, envelope construction, shading design, and others – in the presence of confounding variables such as varying internal loads. (3) The authors investigated the impact of urban context. Since in generalized guidelines the future building site is unknown, the authors tested a method for generating an urban context based on the floor area ratio and maximum building heights of an urban district. These tests support the larger idea of eventually creating a comprehensive, pre-simulated resource for pre-design.

Keywords

Energy Modeling; Parametric Simulation; Urban Context; Passive Survivability; Resiliency; Peak-Load Reduction; Multi-Family Housing

INTRODUCTION

The United Nations expects the world's urban population to nearly double by 2050, increasing from 3.3 billion in 2007 to 6.4 billion in 2050, with much of this growth occurring in developing megacities [1]. Because of this new growth, society cannot afford to simply replicate standard building practices. New buildings must respond to the local climate and urban form, rather than rely on fossil fuels to make up for ill-suited designs. Yet

achieving a high-performance design can be challenging.

Today, design teams rely on computerized energy simulation to help achieve energy performance goals, but that is far from a ubiquitous practice. Design teams not pursuing green rating certification, or teams in regions without local simulation requirements, rarely use energy simulation. The American Institute of Architects stated that U.S. firms had little understanding of the potential energy consumption for more than 40% of their projects [2]. The situation is likely worse in cities with rapid development schedules and limited design budgets.

Many design teams lack the budget or skills necessary to use energy simulation. Research shows that teams who do employ this tool habitually apply the analysis too late in the design process to take advantage of important passive design opportunities [3]. The most influential and cost-effective decisions occur earliest in the project's life [4], and experts suggest that building energy simulation would be more valuable much earlier in the design process [5]. Several researchers even recommend using energy simulation as a pre-design tool [6,7]. At that stage, simulation can assist teams in setting energy performance targets [8], evaluating passive energy strategies, identifying the most influential design parameters, and setting preferred ranges for key design parameters [7].

Firms who do start simulation early bear the cost of the entire customized analysis, starting from scratch. These firms then relegate their results to private client reports rather than a shared database [3]. Therefore, one firm's analysis rarely informs others. The authors propose to create comprehensive design guidelines for high-rise multifamily housing in megacities by utilizing today's computing power and parametric simulation techniques to pre-simulate numerous potential design combinations. The energy simulation results would be translated into comprehensible design guidelines and easily parsed via a web-based interface to assist design teams as a starting point in the decision-making process. One could test the impact of various inputs, similar to the U.S. Department of Energy's (DOE) Building Performance Database [9], except populated with simulation results. The authors will expand the investigation beyond custom geometries, unique specifications, and limited ranges of performance

parameters, to create a resource that can inform multiple teams of architects and policy-makers.

As a first step, the goal of this research was to help establish criteria that would be included in the pre-simulated resource for architects. The authors used computerized energy simulation to test combinations of design parameters on one floor of a prototype multi-family, high-rise (100m+/- [328ft+/-]) residential building. The research included three parts. First, the authors compared the results of prioritizing different energy objectives. Researchers have shown the importance of architectural design on reducing peak energy demand [10, 11] and improving passive survivability, especially in multi-family residential buildings [12, 13]. Here, the authors strove to identify synergies and trade-offs, in terms of early design decisions, when designing for these different energy objectives.

Second, in the spirit of precedent research [14,15], they performed sensitivity analyses to identify the most influential of the tested design parameters, – including building form, window-to-wall ratio, envelope construction, shading design, and others – in the presence of confounding variables such as varying internal loads.

Finally, researchers have shown that urban context affects simulated energy use [16, 17]. However, with generalized pre-design guidance, context must be generalized because the actual project location within the urban fabric is unknown. In addition, neighborhoods are not static and it is difficult to account for future developments. Therefore, the authors analyzed the impact of urban context on the investigated design parameters, and tested a method for generalizing context when the future building site is unknown.

The authors began with three test cities. Beijing and Shenzhen China, which have a growing market for tall buildings, are the second- and fourth-fastest growing megacities globally [18], and represent two unique climates, ASHRAE Climate Zones 2 and 4 respectively. The authors included New York City (also Zone 4), because of available urban context data. In this project, researchers from academia and practice collaborated with the goal of informing real-world architecture.

METHODOLOGY

Software

The authors set up the parametric building and urban context models using Grasshopper, a graphical algorithm editor for the 3D modeling tool Rhinoceros. They used ArchSim, a Grasshopper-based plug-in, to create input files, which were run in the U.S. Department of Energy's simulation engine, EnergyPlus.

Passive Survivability and Peak Load Objectives

The authors identified synergies and trade-offs, in terms of early design decisions, when designing for different energy objectives that may be included in the pre-design guidelines. Included in these objectives are the reduction of Energy Use Intensity (EUI), shaving peak-energy demand, and increasing passive survivability. Passive survivability is a measure of resiliency; the goal is to maintain an indoor temperature as close as possible to comfort conditions in a power outage. To test this, the authors ran each simulation for two weeks. The first week followed a normal operation schedule. Then the heating, cooling, mechanical ventilation, and plug-loads switched off (resembling a power outage) and the simulation ran for an additional week. The chosen two-week simulation period centered around the hottest or coldest (dry bulb) day in the weather file. The authors recorded the indoor temperatures in one thermal zone of the building – the hottest zone in summer and the coldest zone in winter. The authors found the design case in each city that keeps this zone the closest to comfort conditions.

To test the designs for peak loads, the authors simulated each design variant and recorded the hourly (8,760 per year) heating and cooling loads for each case. In each city they found the design case that produced the highest and lowest peak loads for both heating and cooling. The authors used typical meteorological year weather files throughout this research in order to test bad, but not unusually extreme, weather conditions.

Design Parameters

The authors strove to test realistic design parameters based on precedent projects in the test cities. The parameters tested included various early-design-phase decisions, such as building shapes, window-to-wall ratios, envelope constructions, and shading designs, as listed in Table 1. Here, the baseline architectural parameters met ASHRAE 90.1 2010 standards, except for the maximum 40% WWR limitation (because contemporary architecture frequently exceeds this limitation).

For floor plan shape, the authors chose variants from prevailing housing high-rise footprints found in aerial photographs of the test cities and in several residential high-rise precedents. The authors modeled a sensitivity analysis for floor plan shape, consisting of a 1-to-0.6 ratio rectangle (labeled “square,” a 1-to-3.5 ratio rectangle, and a T-shape, each with an approximate area of 1200m² (12,917ft²) and a maximum center-to-glass distance of 10m (33ft). Per simulation best practices [19], each plan was divided into thermal zones by core, perimeter (4.6m [15 ft] wide), and solar orientation. See Figure 1.

The authors also tested solar orientation. For Beijing and Shenzhen, cities without a dominant street orientation, they rotated the building either 0° or 90° with respect to north. In New York they used the prevailing Manhattan street grid and thus tested 29° and 119° with respect to

north.

The authors tested the design parameters with two levels of plug-loads (energy consumed by occupant appliances): (a) a baseline called "Low Internal Loads" per the U.S. DOE's Commercial Prototype Building Models (based on ASHRAE 90.1 2004) and (b) double that value, as a sensitivity analysis [20]. Their diversity schedule is listed in the appendix. Plug-loads are not a design decision per se, because architects have little control over this parameter. However, plug-loads have a high degree of uncertainty and can vary by 100% or more over design estimates [21]. Therefore, the authors tested whether this uncertain variable could influence the selection of other design variables.

The simulations assumed an ideal load system with mechanical ventilation. (For calculating EUI, the authors assumed a heating and cooling coefficients of performance of 1.0.) Testing of natural/mixed-mode ventilation is planned for the next iteration of this research.. See the appendix for a list of other simulation assumptions. In order to investigate the importance of each parameter and inform the future pre-simulated resource for architects, the authors simulated every permutation of the design parameters – 1,296 for each city – as a case study.

Table 1: Parameters Tested

Input Name	Parameter Values
Shape	See Figure 1, 1,200 m ² Plan Area
Orientation	0°, 90° (61°, 151° in New York) counterclockwise
WWR	30%, 45%, 75%
Glazing Type*: U-Value W/m ² K (Btu/h ft ² F) & Solar Heat Gain Coefficient (SHGC)	ASHRAE Climate Zone 4, Beijing, New York: "Glass ASHRAE": U=2.84 (0.50), SHGC = 0.4 "Lower-U Glass": U=1.70 (0.30), SHGC = 0.4 "Lower-SHGC Glass": U=2.84 (0.50), SHGC = 0.2 ASHRAE Climate Zone 2, Shenzhen: "Glass ASHRAE": U=3.97 (0.70), SHGC = 0.25 "Lower-U Glass": U=2.27 (0.40), SHGC = 0.25 "Lower-SHGC Glass": U=3.97 (0.70), SHGC = 0.2
Horizontal Shading	No Shading, Projection Factor: 50%, Projection Factor: 100%
Wall Insulation**: U-Value W/m ² K R-Value (ft ² F hr/ Btu)	"Wall ASHRAE": Assembly U=0.365 (R=15.6) Layers and thicknesses: concrete-0.12m, extruded polystyrene (XPS)-0.09m, concrete- 0.12m "More Insul.": Assembly U=0.22 (R=25.8) Layers and thicknesses: concrete-0.12m, XPS-0.15m, concrete-0.12m
Thermal Mass	"Low Thermal Mass": see exterior wall description above, with .25m (9.8in) thick concrete ceiling and floor "High Thermal Mass": same as above with double thickness concrete in ceiling
Plug-Loads kWh/m ² (kBtu/ft ²)	"Low Internal Loads": 5.5 (1.74) "High Internal Loads": 11 (3.49)

*Glass ASHRAE = ASHRAE 90.1 2010 maximum values.

** Wall ASHRAE = ASHRAE 90.1 2010 Zones 2 and 4 maximum wall assembly U values (same requirements for both zones)

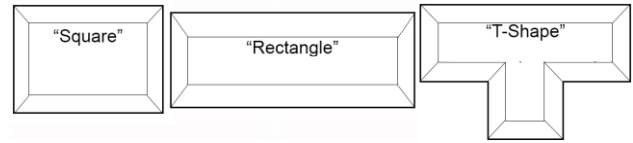


Figure 1. Plan shapes with typical thermal zoning

Context Analysis

Assuming that context matters, researchers would face a challenge when creating generalized pre-design guidance: one cannot know where in a district a future building may be located. Therefore, the authors developed a script in Grasshopper for generalizing urban context based on randomized building heights that maintains a district's Floor Area Ratio (FAR) and height limits (see Figure 2).

As a first step, the authors conjectured whether it is critical to model urban context for this pre-simulated design resource. The presence of neighboring buildings would change energy use, but would it also change the preferred design decisions? To test the impact of urban context, the authors first simulated the 1,296 different design combinations (refer to Design Parameters above) without surrounding buildings, then again within an urban context (the "generalized high-density context" described below). They repeated this study for Beijing, NYC, and Shenzhen, and compared the results with and without context. For this parametric analysis, the authors simulated a lower floor (16m [52ft] above ground) of a high-rise, which would be susceptible to shading from neighboring buildings.

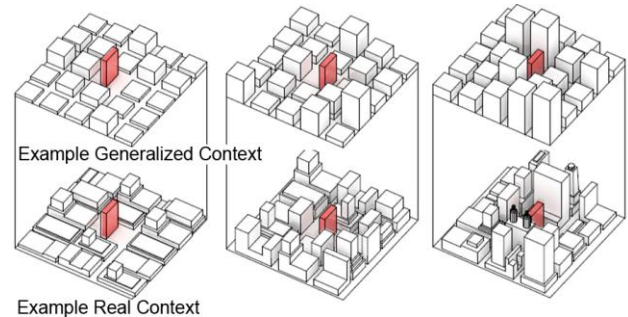


Figure 2. Example Generalized Context

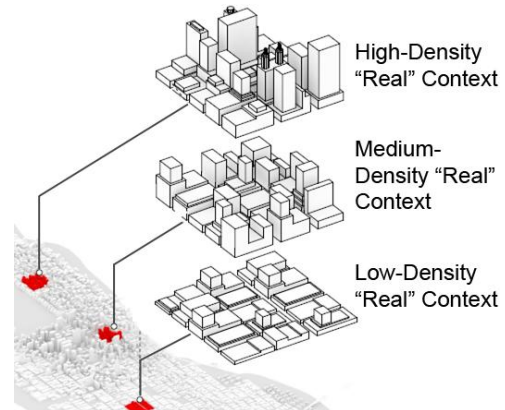


Figure 3: "Real" Context Models in New York

As a second step, to evaluate the accuracy of the authors' Grasshopper script used to generalize the context, they chose three different neighborhoods in NYC as test cases: (1) a high-density context with a Floor-Area-Ratio (FAR) of 15 and a maximum building height limit of 180 meters, (2) a medium-density context with an FAR of 6 and a maximum building height limit of 120 meters, and (3) a low-density context with a FAR of 6 and a maximum height limit of 65m. See Figure 3. In the three NYC locations, the authors chose the design case with the lowest EUI, and simulated it without context, with the generalized context, and with the real existing context. Three floor heights were tested: 16m (52ft), 48m (131ft), and 64m (210ft): a lower, middle, and upper floor of a 100m tower.

Throughout the analysis, the authors only considered the shading impact of neighboring buildings. The authors did not perform energy simulations for these buildings. The potential impact of reflective facades was not considered but could be added in future work.

RESULTS

Design Objectives: EUI, Passive Survivability, Reducing Peak Loads

The case studies are intended to clarify which design objectives are important enough to include, or even expand, and which ones to omit or revise, in a future pre-simulated resource for architects. An initial research question was, did the range of parameters tested produce a substantial difference between the design cases according to each objective?

The early design decisions studied here had a significant impact on the building's EUI in each city. The differences between the best and worst simulated EUI in Beijing, New York, and Shenzhen were 19%, 21%, and 13% respectively. (Unless noted, results include the low plug-load cases only). The authors also found a large difference between the performance of the test cases in terms of peak loads, and a moderate difference in terms of passive survivability. Therefore, one can conclude that within the parameter ranges tested, each of these objectives mattered.

Figures 4 and 5 show example indoor temperature results for the best and worst design cases, while Table 2 shows a summary of the simulation results. One might also wonder whether each objective would lead to different design decisions. The answer is that yes, in each city, the preferred design would indeed change if one designed for peak load reduction, or passive survivability, rather than EUI. Figures 6–8 show the EUI breakdowns for the best

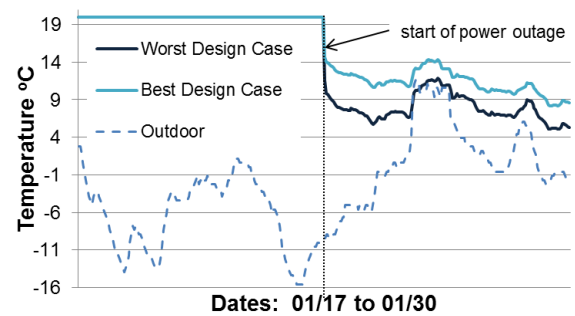


Figure 4: Indoor Temperatures in New York with Simulated One-Week Winter Power Outage, Best and Worst Design

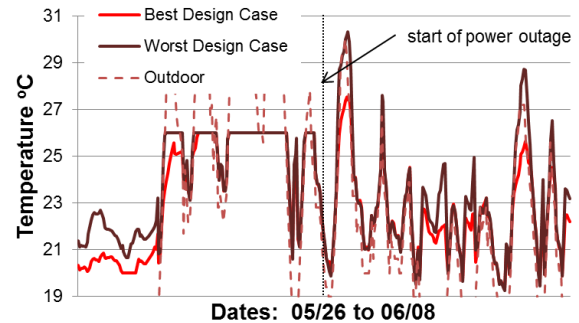


Figure 5: Indoor Temperatures in New York with Simulated One-Week Summer Power Outage, Best and Worst Design

cases for different design objectives. The worst case for EUI is also shown for comparison. Table 4 in the appendix highlights which design parameters would change in order to prioritize each objective. For comparison, Table 5 lists the worst case for each objective.

Table 2: Difference between Best and Worst Cases

	Beijing	NYC	Shenzhen
EUI	19%	21%	13%
Peak Hourly Summer Load	37%	22%	18%
Peak Hourly Winter Load	40%	39%	NA
Extreme Indoor Temp.: Summer delta between best & worst cases	3.7K (6.7°F)	2.8K (5.0°F)	1.4K (2.5°F)
Extreme Indoor Temp.: Winter delta between best & worst cases	3.8K (2.4°F)	3.1K (5.6°F)	NA

Interestingly, the benefit of these specialized designs was minimal in most cases. That is, prioritizing low EUI met the alternate objectives fairly well. Compared to the best cases for these objectives, the EUI-prioritized cases underperformed the peak load reductions by less than 2% and the extreme indoor temperatures by less than 1K (1.8°F). Exceptions are discussed below. At the other extreme, design cases that failed in terms of EUI performed even worse in terms of peak loads. In Beijing, the worst EUI case produced a 34% higher peak heating load and a 20% higher peak cooling load than the best EUI case. (These results were 35% and 18% respectively in New York, and 13% for the peak cooling load in Shenzhen.)

Furthermore, the results indicated that prioritizing alternate objectives had its drawbacks. In Beijing and

New York, the best case for passive summer survivability reduced the average indoor temperature only slightly compared to the lowest EUI case, and not without substantially compromising the EUI performance, which increased by 7% and 8% respectively over the lowest EUI case. By prioritizing peak cooling loads in Beijing and NYC, one could reduce this load by 2% and 3% respectively over the lowest EUI case, but in so doing increase the EUI by the same percentage. This is a substantial annual energy penalty for the peak load benefits.

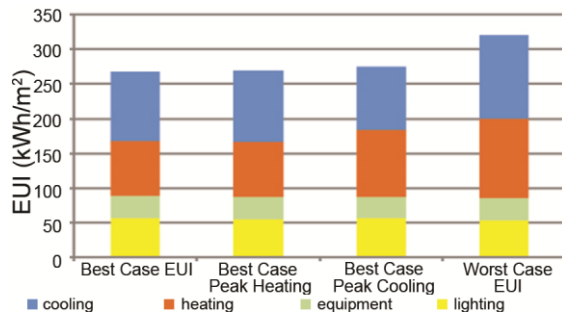


Figure 6: Energy Breakdown of Notable Cases, Beijing

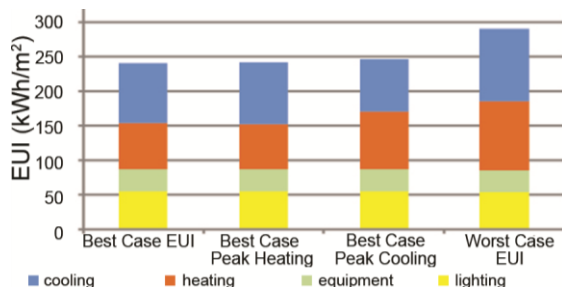


Figure 7: Energy Breakdown of Notable Cases, New York

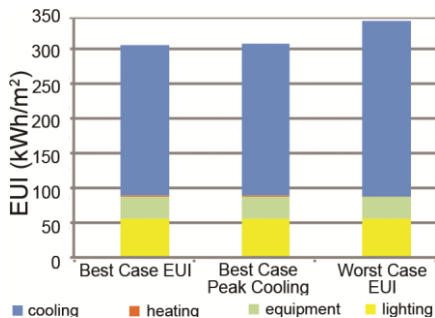


Figure 8: Energy Breakdown of Notable Cases, Shenzhen

Perhaps these results are not surprising in these mixed heating/cooling climates, but prioritizing peak cooling in cooling-dominant Shenzhen also had drawbacks. Here, the lowest peak-cooling-load case decreased the peak load marginally (<1%) compared to the lowest EUI case. Ironically, though, it increased both the EUI and annual cooling load by 2% over the best EUI case. This result highlights the problem of designing for a certain peak hour (especially when this moment may or may not prove to be the peak condition in future years.)

In summary – even though the design parameters tested could have a large impact on peak loads and a moderate impact on passive survivability – if one does a good job designing for low EUI with these parameters, it is difficult to do much better for peak loads or passive survivability by specifically prioritizing these objectives.

Sensitivity of EUI to Test Parameters

To inform the methodology for a future pre-simulated design resource, the authors investigated which design parameters made a substantial impact on EUI. For each category, e.g. WWR, the authors found the median simulated EUI for the design iterations in each bin, e.g., 30%, 45%, and 75% WWR. They then calculated the percentage difference between the median EUI result in the best and worst performing bin. The results are shown in Figure 9 for each city with the generalized high-density urban context (dashed) and without context (solid). Of the parameters tested, EUI was most sensitive to WWR, glass type, building shape, building orientation, amount of wall insulation, and thermal mass, in that order. (The interaction between urban context and parameter impact/selection will be discussed later.)

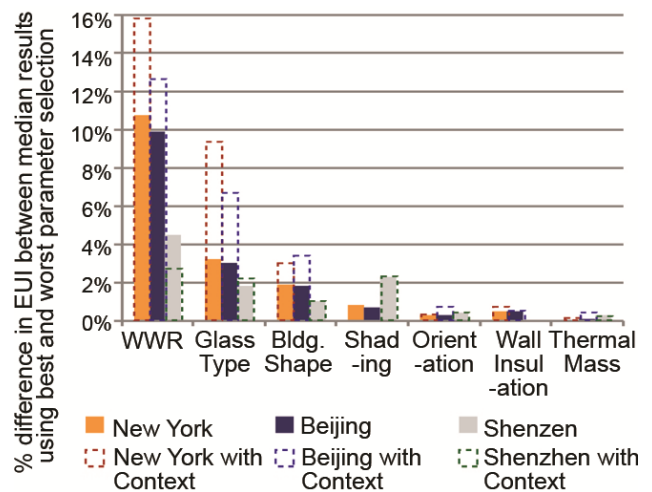


Figure 9: Sensitivity of EUI to Design Parameters

Changing the levels of thermal mass did not produce a large impact on the simulated results. Two factors likely contributed to this result. First, even the "low mass" option included exposed concrete surfaces, and thus already had high thermal mass relative to the available range of contemporary construction choices. Second, due to the details of the ArchSim export and the EnergyPlus settings, the added thermal mass in the "high mass" option was not exposed to direct sunlight, which limited its simulated effectiveness.

Plug-loads were indeed found to be a confounding variable, in that the use of "high" versus "low" plug-loads did affect the preferred selection of other design parameters (in two of the three cities). In New York, higher plug-loads led to a preference for lower thermal mass, and in Shenzhen, higher plug-loads led to a

preference for less wall insulation. However, the energy impact of these design decisions was minimal in an otherwise well-designed case. In the lowest EUI case, subsequently changing between high or low thermal mass in New York, and more or less insulation in Shenzhen, resulted in a difference of less than 1% in the resulting EUI. In the future, the authors will use these results to refine/expand/replace the sets of test parameters. For example, more variants of important parameters such as WWR, glass type, and building shape will be included.

Impact of Urban Context

Would urban context affect the early design decisions studied here? Including the generalized high-density urban context in the simulations increased the heating load by 5% and 6%, while decreasing the cooling load by 6% and 9%, in Beijing and NYC, respectively, compared to iterations with no context. In Shenzhen, the cooling load decreased by 4% with the addition of context. Therefore, the impact of urban context on building loads was substantial. Results for NYC are shown in Figure 10. **Error! Reference source not found..**

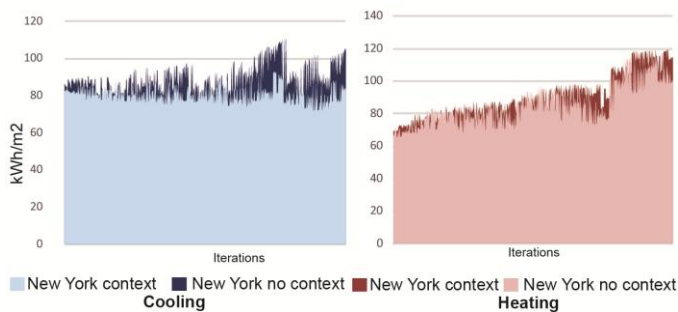


Figure 10: Impact of Context on Heating/Cooling in NYC

Importantly, context also affected the preferred design decisions. Figures 11 and 12 show how the energy consumption and preferred design parameters changed in New York and Shenzhen depending on the presence of neighboring buildings. For example, in Shenzhen, with the presence of urban context, the preferred WWR actually increased to 75%. (The preferred Beijing parameters were nearly the same as New York's, with a slight difference in shading design, as listed in Table 4.)

On the other hand, in each city, some preferred parameters (for example, glass choice) did not change regardless of the presence of urban context, as listed in **Error! Reference source not found..** The winning glass selections show that in the cool climates, lowering the U-value was always the more important glass characteristic, whereas in the warmer climate, lowering the SHGC was always paramount.

In summary, including urban context matters. Because several important design decisions changed depending on whether or not context was included, pre-design guidance (and perhaps energy code requirements) should account for the effects of urban context.

The next question is: how much do the details matter? (The following context analysis results are based on tests with the lowest EUI case only. The impact of context details would be even larger in a more vulnerable building design, such as one with 75% WWR.) Nevertheless, floor heights mattered. The difference in heating and cooling loads change between 2% and 4%, in each NYC context, depending on whether one was considering a lower or an upper floor. Urban density (neighboring building height) also mattered. At the 16m floor elevation, when changing from a low-density to a high-density context in NYC, cooling loads decreased and heating loads increased by 3% each. Importantly, these results also impacted early design decisions.

Generalized urban contexts are one method for modeling this important, but unknown, entity in pre-design. How did the generalized contexts perform? As expected, the generalized contexts, based on FAR and maximum building heights, produced slightly different results than the “real” contexts. However, the differences were small. In each of the nine cases, (three urban densities times three floor heights) the differences in the heating and cooling loads between the “real” and generalized context cases were less than 1% (as opposed to a 3% error if no context was included). Therefore, creating a generalized urban context based on neighborhood characteristics produced substantially better results than ignoring urban context altogether.

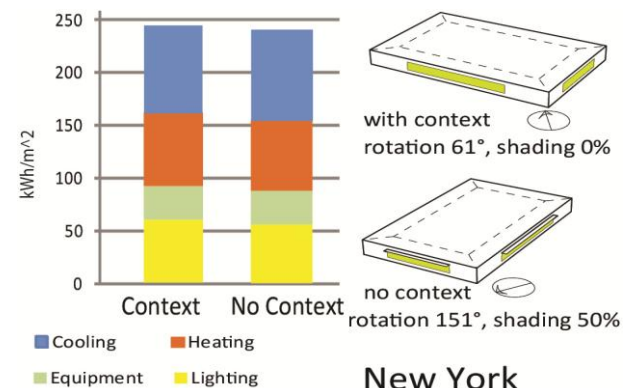


Figure 11: Lowest EUI Case with and without Context, NYC

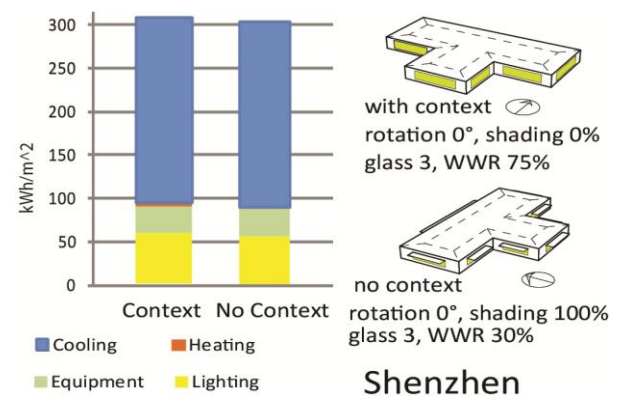


Figure 12: Lowest EUI Case with and without Context, Shenzhen

Table 3: Preferred Parameters Unchanged by Urban Context

Beijing	Orientation, 30% WWR, Lower-U Glass, Shading, More Insul. Wall
New York	30% WWR, Lower-U Glass, More Insul. Wall, high internal mass
Shenzhen	Lower-SHGC Glass, high internal mass

DISCUSSION

Potential for Generalized Pre-Design Guidance

The results here confirm the important impact of early architectural design decisions on building energy performance. When starting design on a low-energy project, it would be helpful for architects to have guidance, such as which design parameters can potentially make a large impact on energy performance in their climate/city/urban district. Yet many teams lack the budget or skills necessary to use energy simulation in early design phases. With parametric simulation, researchers can test a potentially large enough solution space to provide a pre-simulated, pre-design resource for multiple architecture teams.

This research was the first step toward refining the goals and methodology for creating such a resource. An expansion of this study will link pre-simulated results sets with user selection fields to offer end-users pre-simulated design feedback. Users will be able to select various design choices and see how their changes affect energy performance. Such a web-based, searchable resource will aid design teams who are starting high-rise residential design in certain cities. It will also establish a replicable methodology capable of producing large result sets that can provide value to other designers and researchers.

Here, the authors tried to understand the “design significance” of urban context, design parameters, and differing energy objectives. They defined “design significance” by asking, does this variable change the choice a designer should make, and would that selection then significantly impact the energy results? Consequently, these results will be used to establish which parameters will be included in the design guidelines. For example, varying plug-loads had a very large impact on EUI, and differing levels of plug-loads resulted in differing preferences for other parameters. However, the resulting EUI difference between the preferred design choices based on high or low plug-loads was not significant. Therefore, this variable will not be included.

Other Objectives: Passive Survivability, Reducing Peak Loads

In this study, preferred design decisions changed depending on the energy objective selected, but the performance advantage of designing specifically for peak load or passive survivability – rather than annual energy consumption – was small. In short, designing for low EUI met the other objectives reasonably well.

Here, the authors chose to study these impacts in typical weather years in order to design for high probability conditions. However, as urban growth strains existing infrastructure and the frequency and magnitude of weather emergencies increases, designers may have an ethical imperative to consider extraordinary weather events. Therefore, the authors plan to test these results using extreme and future weather files in their upcoming research. Testing with more extreme weather events would likely widen the disparity between the performance of the lowest EUI case and those cases designed specifically for passive survivability.

The Shenzhen results demonstrated the trade-offs encountered when designing for a certain peak moment, because the design for lowest peak cooling load actually failed to produce the lowest overall cooling load. Therefore, targeting one peak hour may not be the best approach. Moreover, from an environmental perspective, the most important time to reduce demand is during the peak periods experienced at the grid scale, not the building scale, so future research should consider the typical grid-scale peak periods instead.

Urban Context

The results here supported the notion that urban context matters in low-energy design. The presence of the high-density urban context affected the heating and cooling loads by 4% to 9%, and changed the preferred design parameters. Therefore, one needs to consider urban context in generalized design guidelines (and ideally, energy code policy). The approach to estimating urban context presented here – randomizing neighboring building heights based on FAR and maximum height – provided more realistic results than ignoring the context altogether.

In this research, the algorithm produced one context with randomized building heights. In the future the authors will repeat this process numerous times to control for idiosyncrasies. Then they will run all simulation studies with urban context.

China is in the process of planning new cities from the ground up. In situations like this, urban density and form can be design variables, rather than static parameters, and the method of parameterizing urban context presented here can offer testing capabilities to inform design at the urban scale as well.

Future Work

Simulation Parameters

In the future, the authors plan to consider natural and mixed-mode ventilated buildings, which are especially prevalent in residential architecture. They also plan to consider the impact of prevailing HVAC components and efficiencies. Here, the settings portrayed a relatively high occupant density, primarily present in the evening/night, with high illuminance targets. No window blinds have

been considered. Due to the EnergyPlus settings, the mechanical systems ran constantly with no set-back temperatures. Future research will investigate the impact of changing each of these parameters and will take into account cultural impacts in each city. For example, different occupant densities may be appropriate in different cities. As noted, here the low-thermal mass and high-thermal mass parameters were relatively similar, and the authors plan to include a lighter-weight construction option in the future. The thermal zoning strategy here was a simplification of reality, which would be broken into more zones. The impact of this simplification, especially on indoor temperatures will be studied and the number of zones expanded if necessary.

Research Expansion

The designs for Beijing and New York, with their similar climates, performed very similarly – i.e., the preferred design choices only differed in parameters found to have a minor impact on EUI. Therefore, future research will investigate the feasibility of applying results to different cities within a climate zone.

Future research will also evaluate the feasibility of this pre-design simulation approach by testing against real-world case studies. The researchers will explore the benefits and shortcomings of this approach in lieu of traditional analysis methods, with regard to accuracy, practicality, and cost-effectiveness. The work will be expanded to other climates and possibly later to other building types. The web interface could expand to create a repository of predictive modeling results, so that others could contribute to the resource. Finally, the authors hope to demonstrate that a pre-simulated framework can lead to multiple creative solutions, and that its role is to inspire rather than replace the brain of the designer.

CONCLUSION

Through parametric energy simulation, this research explored energy performance in multi-family housing in New York, Beijing, and Shenzhen as a first step toward creating a comprehensive pre-simulated resource for early-design of residential high-rise architecture in megacities. The authors tested a method to generalize urban context and investigated the impact of methods, design parameters, energy objectives, and confounding variables, providing results which can be used to inform future research.

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APPENDIX

Other Model Assumptions

Weather data:

USA_NY_New.York-Central.Park_TMY3.epw,
CHN_Guangdong.Shenzhen.594930_SWERA.epw,
CHN_Beijing.Beijing.545110_IWEC.epw.

Floor: Adiabatic (The simulated residence is bordered by other conditioned residences above and below.)

Roof: Adiabatic

Lights:

1. Continuous Dimming
2. Power-Density: 10.76 kWh/m² (3.41 kBtu/ft²) per ASHRAE 90.1 2010
3. Illuminance Target: 500 lux (46 footcandles)

Occupants Density: 0.2 person/m² (0.019 person/ft²)

Conditioning:

1. Heating Set Point: 20°C (68°F)
2. Cooling Setpoint: 26°C (79°F)
5. Mechanical Ventilation: On
6. Min. Fresh Air per Person: 0.001 m³/s-person (2.12 ft³/min-person)
7. Min. Fresh Air per Area: 0.001 m³/s-m² (0.197 ft³/min-ft²)
8. Economizer: No
9. Heat Recovery: None

Ventilation:

1. Infiltration: 1 Air Change per Hour (ACH)
2. Scheduled Ventilation: 0.6 ACH
3. Natural Ventilation: No
5. Hybrid Ventilation: No

Schedules:

The following occupancy schedule was used seven days per week, based on the US DOE's Prototype Models [20] (Models are based on ASHRAE 90.1. 2004). All other operating schedules were based on this schedule. The diversity factor for each hour from 1:00 to 24:00 is as follows: 1,1,1,1,1,1,0.9,0.7,0.4,0.2,0.2,0.2,0.2,0.2,0.2,0.3, 0.5,0.9,0.9,0.9,1,1,1

Table 4: Parameters of BEST Case for low EUI, and Other Objectives (Where Different)

BEST Case for:	Beijing	New York	Shenzhen
EUI	square, 0°, 30% WWR, lower-U glass, shading 0%, more wall insul., high thermal mass	square, 151°, 30% WWR, lower-U glass, shading 50%, more wall insul., high thermal mass	T-shape, 0°, 30% WWR, lower - SHGC glass, shading 100%, more wall insul., high thermal mass
Peak Heating*	low thermal mass	shading 0%	NA**
Peak Cooling*	T-shape, lower-SHGC glass, shading 100%	T-shape, lower-SHGC glass, shading 100%, low thermal mass	lower-U glass
Passive Survivability Winter*	T-shape, 90°	shading 0%	NA**
Passive Survivability Summer*	T-shape, 90°, 45% WWR, lower-SHGC glass, shading 100%, less wall insul.	(Same as Peak Cooling Case)	Rectangle, 90°, less wall insulation, low thermal mass

* Only parameters that differ from EUI best case above are listed here.

**Designing for winter passive survivability and reducing peak heating load is unnecessary in this climate.

Table 5: Parameters of WORST Case for low EUI, and Other Objectives (Where Different)

WORST Case for:	Beijing	New York	Shenzhen
EUI	Rectangle, 90°, 75% WWR, Glass ASHRAE, shading 100%, less wall insul., high thermal mass	Rectangle, 61°, 75% WWR, Glass ASHRAE, shading 0%, less wall insul., high thermal mass	Rectangle, 90°, 75% WWR, lower U glass, shading 0%, more wall insul., low thermal mass
Peak Heating*	0°, low SHGC glass	Low SHGC glass, shading 100%	NA**
Peak Cooling*	0°, shading 0%	Same as worst EUI	glass ASHRAE, less wall insul., high thermal mass
Passive Survivability Winter*	T-shape, 0°, low SHGC glass, low thermal mass	T-Shape, 151°, Low SHGC glass, shading 100%, low internal mass	NA**
Passive Survivability Summer*	T-shape, 0°, lower-U glass, shading 0%, more wall insul., low thermal mass	T-shape, 151°, Low U-value glass, low thermal mass	T-Shape, high thermal mass

* Only parameters that differ from EUI worst case above are listed here.

**Designing for winter passive survivability and reducing peak heating load is unnecessary in this climate.